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ITHACA, N.Y.

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THE DEPTH OF THE LUNAR DUST LAYER

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PACKING PROPERTIES OF FINE POWDERS AND THE DEPTH OF THE LUNAR DUST LAYER

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Bruce Hapke

(NASA Grant NsG-382)

Previous experimental and theoretical studies by the author (Hapke and VanHorn, 1963; Hapke, 1963) of surfaces which reflect light like the moon strongly support the hypothesis that the lunar surface is covered with a layer of fine rock dust. The material in this layer is in an extremely uncompacted state, having a bulk density of the order of one-tenth that of solid rock.

Such photometric studies can give information concerning only the uppermost centimeter or so of the lunar soil. However, analyses of radio frequency observations indicate that extensive areas of the moon may be covered to depths of many meters by a substance which is also much less dense than solid rock. From the radar reflectivity of the lunar surface Evans (1962) infers a dielectric constant of $K = 2.7$, while Troitsky (1962) estimates $K = 1.6$ on the basis of radio thermal observations. Since the dielectric constants of stoney meteorites and of terrestrial rocks range from about 4 to 45 (Fensler, et al, 1962) it is clear that the lunar soil is quite underdense to at least depths to which RF radiation can penetrate; Troitsky estimates this depth to be of the order of 10 wavelengths in the 1 - 100 cm wavelength range. It is very reasonable to suspect that the underlying materials might be identical with those exposed at the surface. Such deep layers of dust would be in accord with the suggestions of Gold (1955 and 1963).

It is sometimes argued that since the materials appear to be so much less dense than rock or sand it is not possible that they could be finely-pulverized rock dust. It is the purpose of this note to report the results of measurements on terrestrial powders, which show that fine dust resists compaction sufficiently well so that a layer of rock powder of considerable depth on the moon could maintain itself in the low density state that seems to be required by the radio observations. These measurements were performed by Mrs. J. Morris in the author's laboratory.

A sample of dunite (Jackson County, N. Car.) was ground in air to an average particle size less than 10μ. As discussed in the previous paper (Hapke and Van Horn, 1963), for grains of this size the adhesive surface forces acting between grains are greater than the weight of the grains and strongly influence the packing properties of the material. The rock dust was baked in an argon atmosphere at 750° C for 17 hours in order to remove all superficial layers of grease and water. The sample was then cooled to room temperature and sifted through a 400 mesh screen into a cylinder of 1" diameter until a depth of 1/2" was built up. A piston of the same diameter as the cylinder was used to compact the dust. The change in density of the material was measured as a function of applied pressure. At all times the sample remained in an argon atmosphere.

The data so obtained was then integrated numerically, assuming hydrostatic equilibrium and lunar gravity, to give the compressive stress and density profiles of a hypothetical lunar soil in which the pressure at any depth is equal to the weight of the overlying layers and which has packing properties similar to the dunite. A second sample of baked dunite was sifted and then placed in an atmosphere saturated with H_2O vapor for 21 hours prior to measuring its resistance to compression. A third sample was sifted and measured without either baking or exposing to water vapor. Lunar soil profiles were also calculated for these samples. The results of these measurements and computations are shown in Figures 1, 2, and 3.

It is of interest to note that the adsorption of water vapor onto the dunite grains evidently resulted in a cementing action which strengthened the bonds between grains and thus increased the resistance to compaction of the material.

The effect of strengthening the intergrain forces is also illustrated by similar measurements on Portland cement. Ordinary commercial Portland cement powder was sifted in air at room temperature into the cylinder and exposed to water vapor for varying times prior to measuring its compressibility. This data and the corresponding lunar soil profiles are given in Figures 4, 5, and 6.

These measurements show that if some sort of process is operative on the moon which can transport fine dust from higher areas and deposit it gently in depressions, the resulting sediments could be uncompacted to appreciable depths. The electrostatic transport mechanisms proposed by Gold (1955 and 1962) would be in the category of such processes. Impacts of meteorites of the order of milligram masses and larger would probably tend to compress the dust, so that the actual density profile of the lunar sediments would depend on the flux of such meteorites relative to the transport rate.

The data for the dunite is especially relevent since the lunar surface may consist of ultrabasic rocks of composition similar to dunite. As Figure 3 shows, at the surface of a dunite-like lunar deposit the bulk density would be about 0.3 g/cc and would increase to about 0.5 g/cc at a depth of the order of one foot; due to the weight of overlying layers the density would continue to increase with depth until at 100 feet below the surface it is about 1.0 g/cc. Increasing the intergrain forces allows the dust to support a greater pressure without compacting, and thus a lower bulk density would be maintained to greater depths on the moon.

There are several reasons for believing that intergrain bonds are stronger on the moon than in the laboratory:

(1) The particles on the moon have been exposed to high vacuum and to the sputtering action of solar corpuscular radiation. Thus the surfaces of the particles in the top layers of the soil will be largely free of contaminating films and the adhesive effects will be enhanced.

(2) Particles under the top layers will have been touching each other undisturbed for long periods of time and it is possible that surface diffusion will allow a limited amount of cold-sintering to take place.

(3) Volatile substances, such as water vapor, are undoubtedly continuously outgassing from the interior of the moon, and adsorption of these substances on the grains will increase the bond strength in the manner demonstrated.

(4) Recondensation at the bond sites of matter vaporized by micrometeoritic impacts and sputtered by solar corpuscular radiation will also increase the bonding. These effects would probably cause the lunar sediments to be rather crunchy.

Firsoff (1961) has objected to a covering of finely-pulverized dust on the moon on the grounds that the thermal conductivity of rock powder in vacuo might be too low. However, at the relatively low temperatures which prevail on the lunar surface the heat transfer properties of the lunar dust will clearly be strongly affected by the area of real contact between the dust grains. The thermal conductivity can very likely be increased by at least an order of magnitude by the same processes which will increase the intergrain bonds. Hence Firsoff's objection has no validity.

Extensive, deep deposits of dust on the lunar surface appear to be compatible with all the radio-frequency, infra-red and optical observations of the moon which have been obtained to date. At present these observations are insufficient to decide between models of the lunar surface which suppose it to consist of rock foam or similar porous materials covered with a thin layer of dust and those which assume that deep deposits of rock powder are prevalent.

ACKNOWLEDGEMENTS

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CAPTIONS FOR FIGURES

Figure 1. Density as a function of normal pressure for dunite rock flour.

Figure 2. Compressive stress as a function of depth below the surface for hypothetical lunar dunite soils. This figure shows the weight of overlying layers which the layer at a given depth is bearing.

Figure 3. Bulk density as a function of depth below the surface for hypothetical lunar dunite soils.

Figure 4. Density versus normal pressure for commercial Portland cement powder. The times next to the curves are the duration of exposure of the sample to H_2O vapor prior to compression.

Figure 5. Compressive stress versus depth below the surface for hypothetical lunar cement soils. The 10 hour curve was obtained by interpolating the data of Figure 4.

Figure 6. Bulk density versus depth below the surface for hypothetical lunar cement soils.

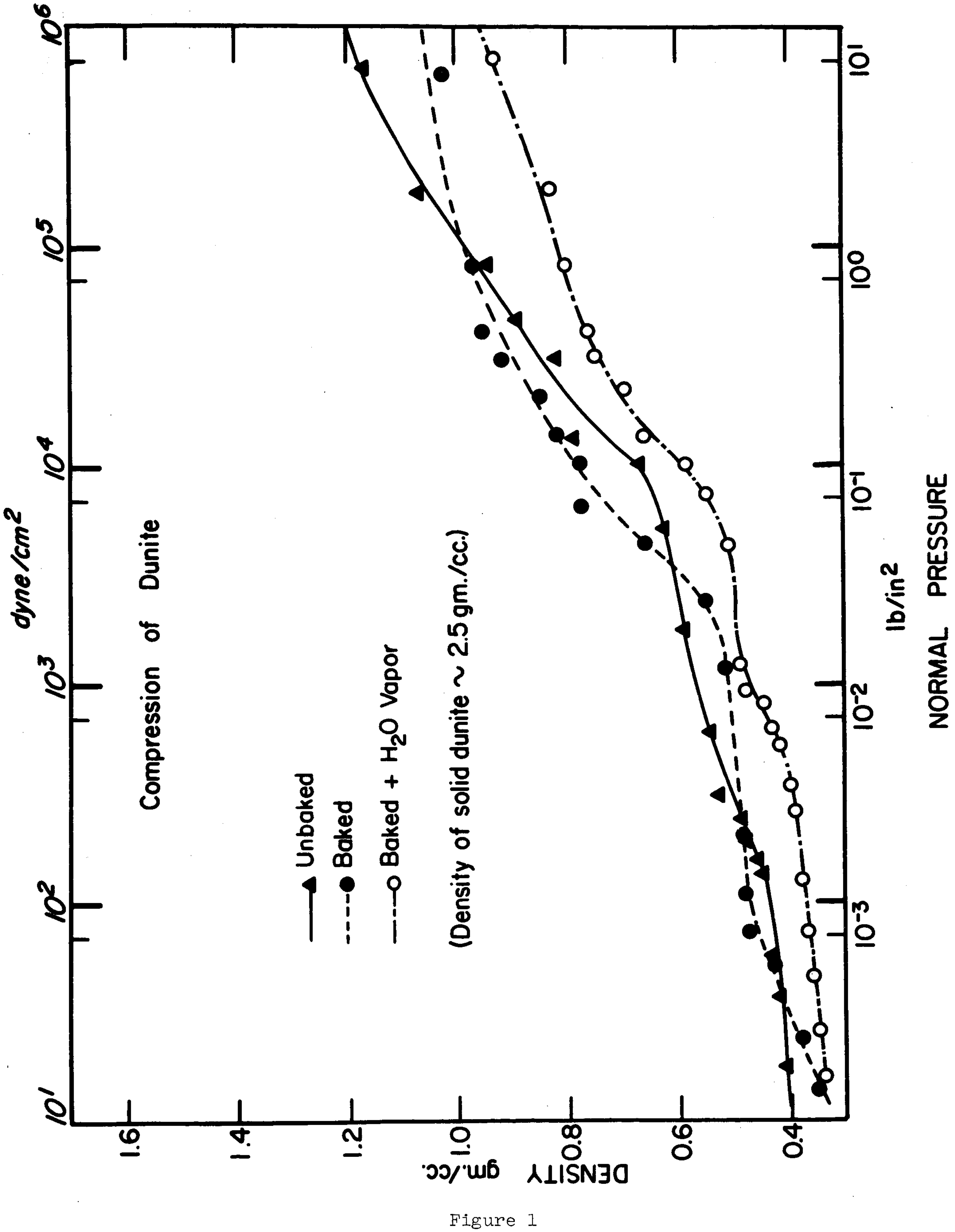
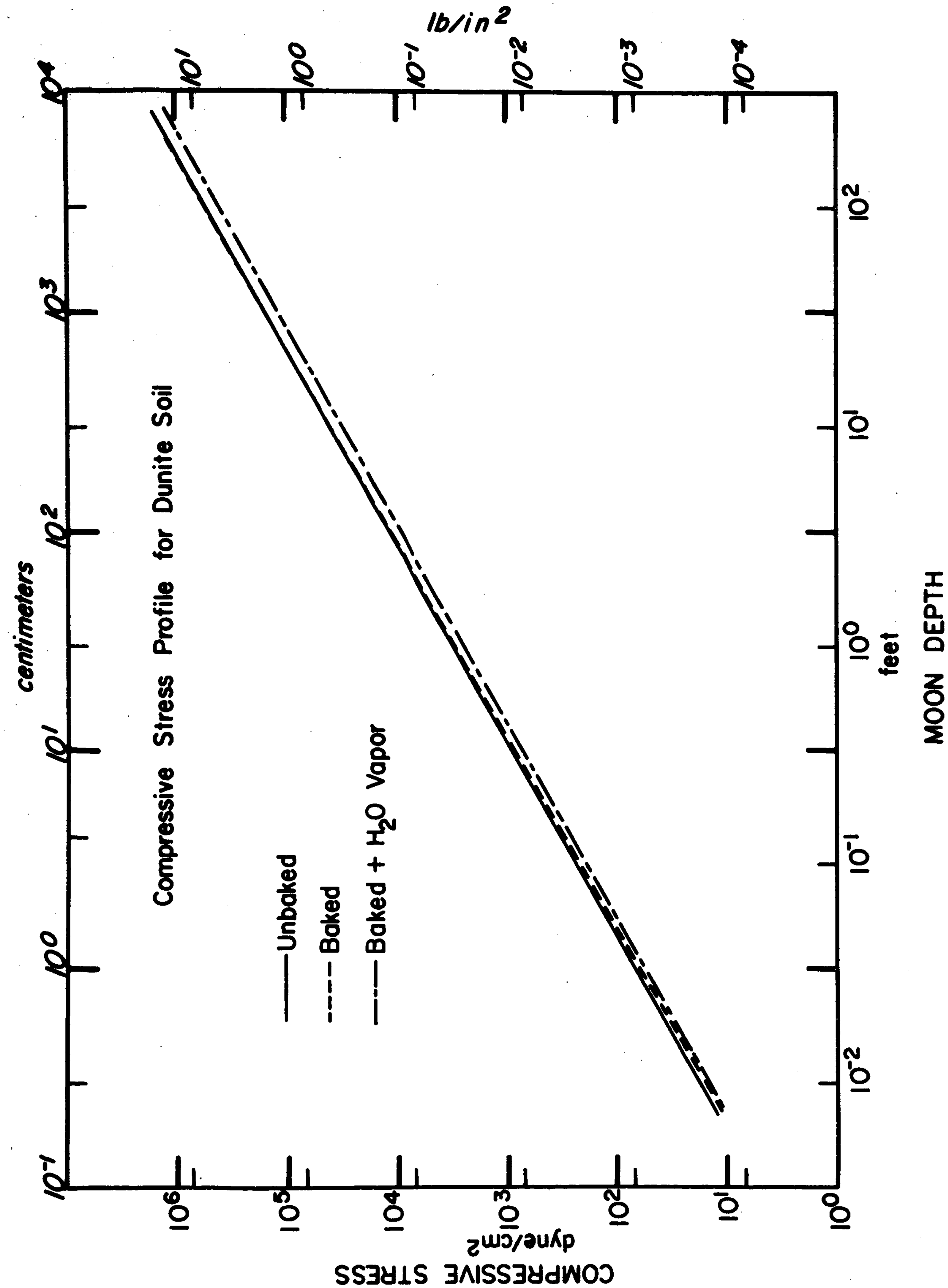
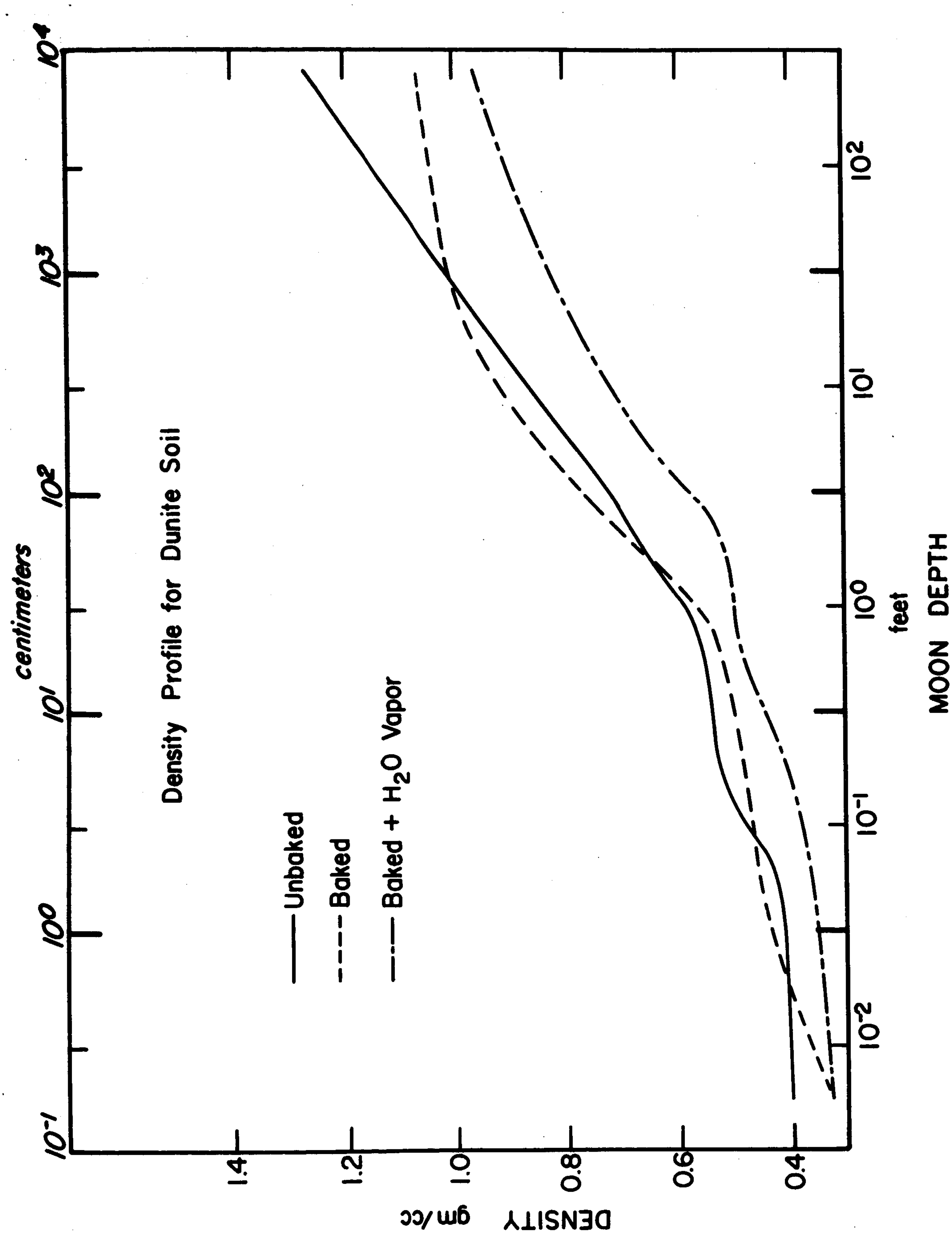

Compression of Dunite
dyne/cm^2
10^1
10^2
10^3
10^4
10^5
10^6
Unbaked
Baked
Baked + H_2O Vapor
(Density of solid dunite ~ 2.5 gm./cc.)
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
lb/in^2
NORMAL PRESSURE
DENSITY gm./cc.
1.6
1.4
1.2
1.0
0.8
0.6
0.4

Figure 1



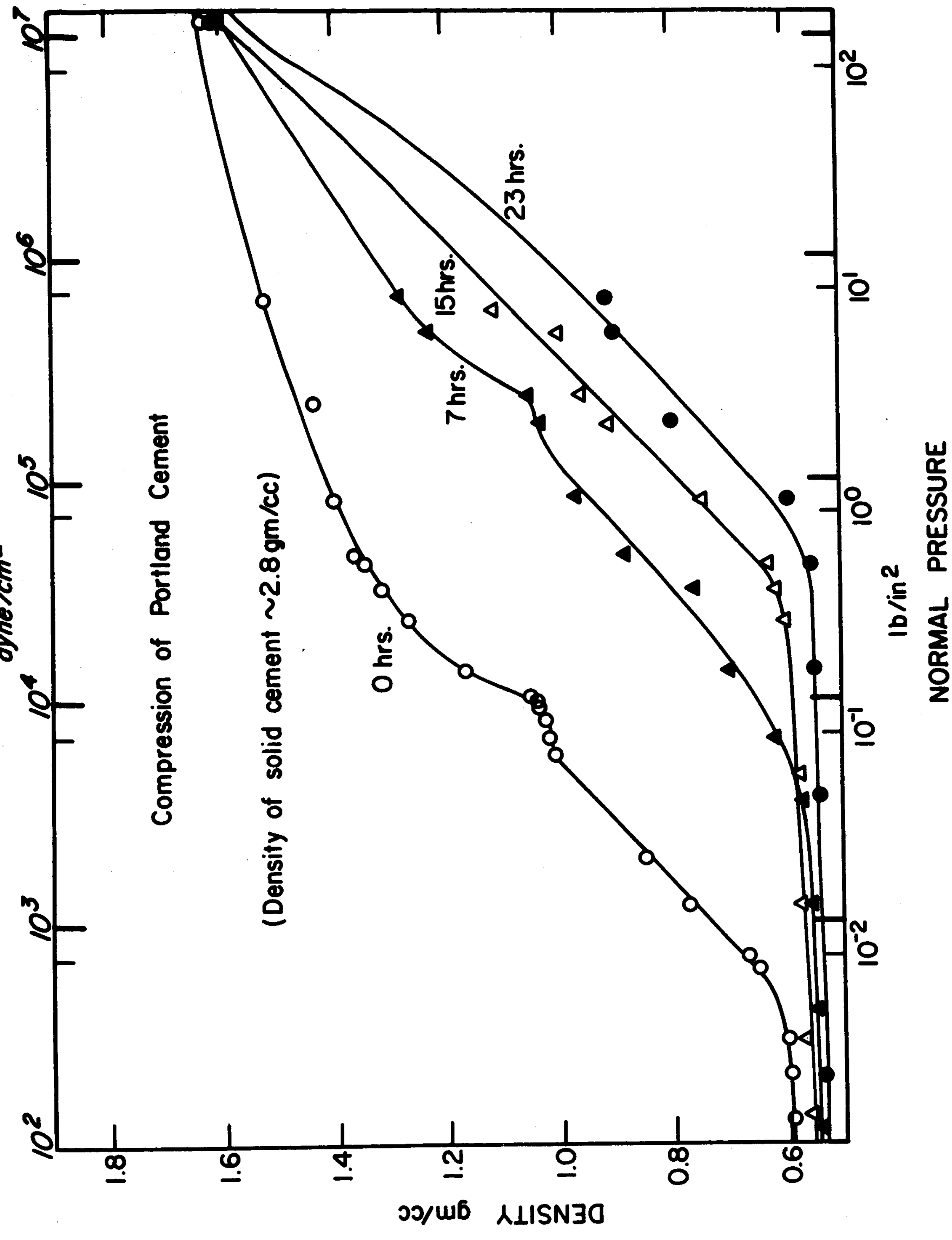
Compressive Stress Profile for Dunite Soil
Unbaked
Baked
Baked + H_2O Vapor
centimeters
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
lb/in^2
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
feet
MOON DEPTH
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
dyne/cm^2
COMPRESSIVE STRESS

Figure 2



Density Profile for Dunite Soil
Unbaked
Baked
Baked + H_2O Vapor
centimeters
10^{-1}
10^0
10^1
10^2
10^3
10^4
feet
10^{-2}
10^{-1}
10^0
10^1
10^2
MOON DEPTH
DENSITY gm/cc
0.4
0.6
0.8
1.0
1.2
1.4

Figure 3



Compression of Portland Cement
(Density of solid cement ~2.8 gm/cc)
dyne/cm2
10^2
10^3
10^4
10^5
10^6
10^7
lb/in2
10^-2
10^-1
10^0
10^1
10^2
NORMAL PRESSURE
DENSITY gm/cc
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0 hrs.
7hrs.
15hrs.
23 hrs.

Figure 4

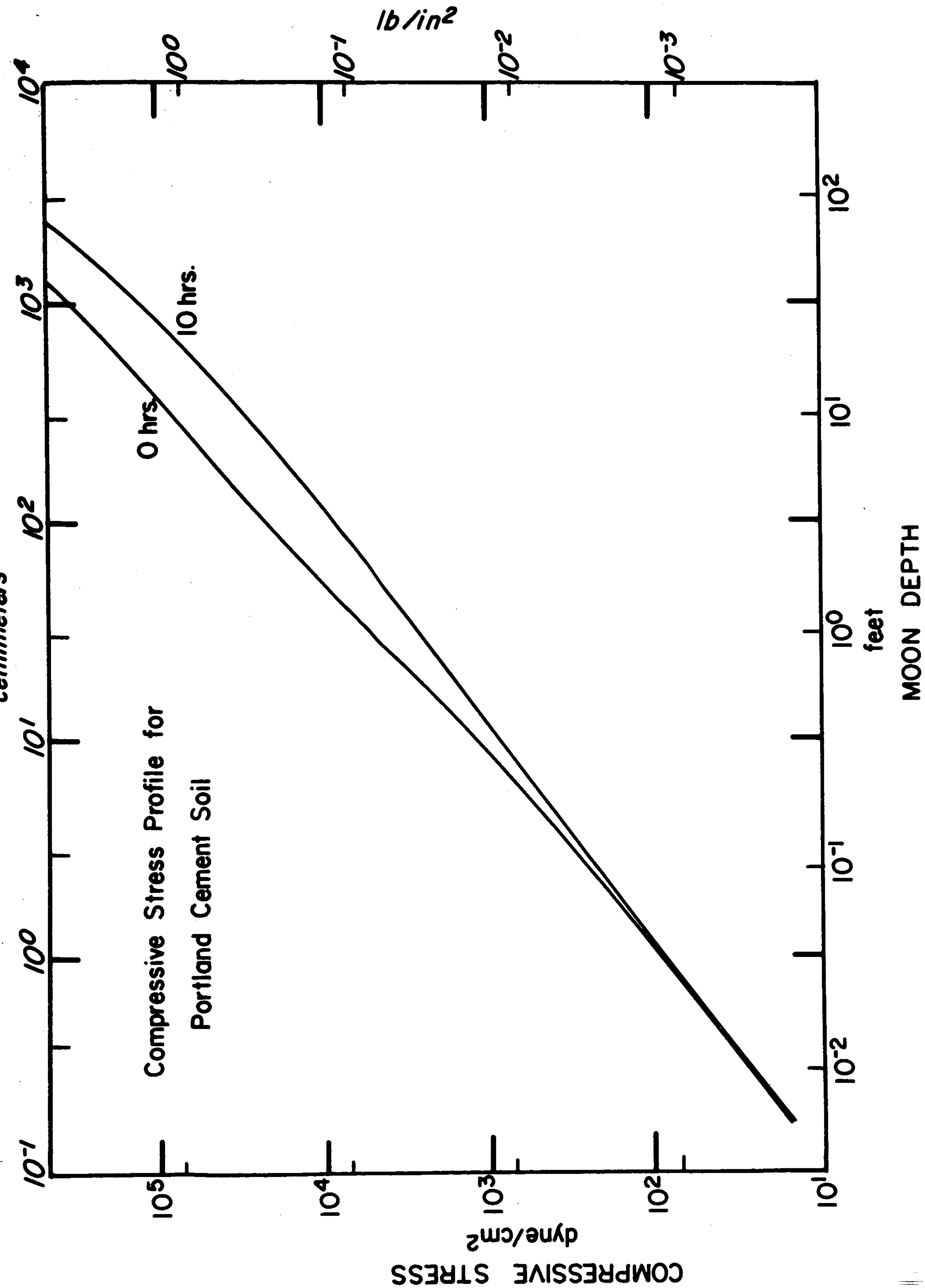

Compressive Stress Profile for
Portland Cement Soil
10 hrs.
0 hrs.
centimeters
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
lb/in^2
10^{0}
10^{-1}
10^{-2}
10^{-3}
MOON DEPTH
feet
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
COMPRESSIVE STRESS
dyne/cm^2
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}

Figure 5

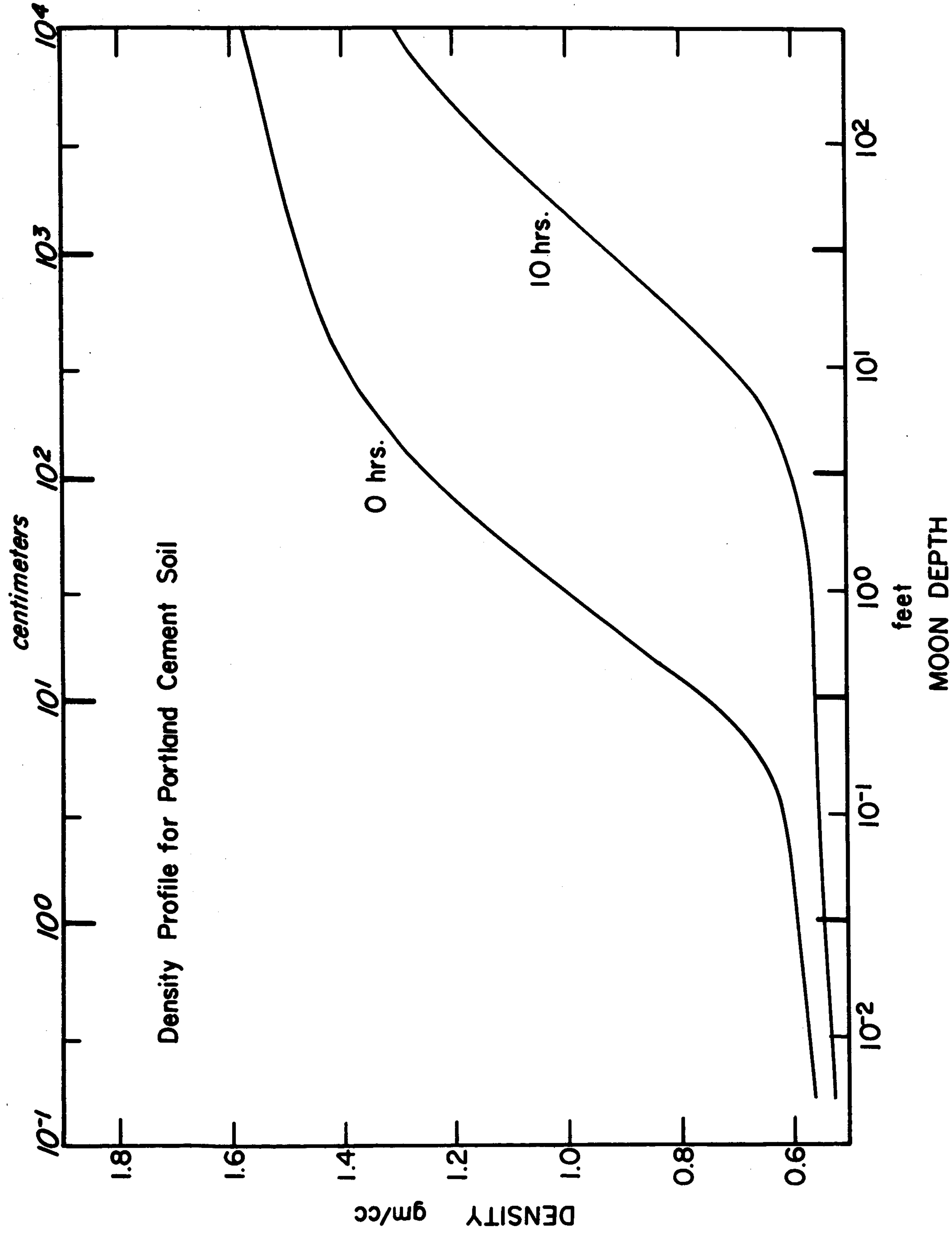

Density Profile for Portland Cement Soil
centimeters
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
0 hrs.
10 hrs.
DENSITY gm/cc
1.8
1.6
1.4
1.2
1.0
0.8
0.6
MOON DEPTH
feet
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Figure 6